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MEMORANDUM REPORT ARBRL-MR-02987

(Supersedes IMR No. 602)

THE HUGONIOT FOR 90W-7Ni-3Fe TUNGSTEN ALLOY

George E. Hauver

February 1980

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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Hugoniot; tungsten-alloy; shock wave; shock velocity; free-surface velocity; elastic wave; elastic precursor; plastic wave.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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The Hugoniot for 25-percent swaged tungsten alloy composed of 90W-7Ni-3Fe has been established at pressures from 17.5 to 184.5 GPa. Within this pressure range the shock velocity is linearly related to the particle velocity by the expression, $U_p = 3.744 + 1.522u_p$, where the velocity unit is km/s.

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I. INTRODUCTION

The Hugoniot for tungsten alloy composed of 90W-7Ni-3Fe has been established by tests conducted at shock pressures from 17.5 to 184.5 GPa. Test specimens 3.0, 6.0, and 12.0mm thick were prepared from rod stock which had been swaged to reduce its cross-sectional area by 25 percent. The mean density of these specimens was 17.068 Mg/m^3 with a standard deviation of 0.045 Mg/m^3. This alloy is a two phase material which consists of tungsten particles in a matrix composed predominantly of iron and nickel. The 25-percent swaging strain hardens the matrix and produces some elongation of the tungsten particles; the hardness of test specimens was Rockwell C 41-43. A radiographic examination of similar tungsten alloy specimens for fracture tests revealed density variation which suggested matrix depletion during the sintering process[1]. Hugoniot specimens, included in a later radiographic examination, also displayed density variation. Further density measurements performed by the Oak Ridge Y-12 Plant[2] indicated density variation of almost seven percent or roughly 1.2 Mg/m^3.

II. EXPERIMENTAL CONSIDERATIONS

From the Hugoniot Elastic Limit to approximately 60 GPa the shock wave in this material consists of an elastic precursor followed by a plastic wave; at higher pressures the plastic-wave velocity exceeds the precursor velocity and a single wave exists. Symmetrical impact experiments were performed at low pressures where a precursor wave is present. Quartz stress gages were used to examine the precursor in several initial experiments, and VISAR interferometry similar to that developed by Barker and Hollenbach[3] was used in later experiments to provide a continuous measurement of free-surface velocity from precursor arrival until the final maximum velocity in the plastic wave. Impact by explosively accelerated metal plates was used to provide the highest test pressures where the plastic-wave velocity exceeds the precursor velocity. At the highest pressures, average shock wave and free-surface velocities were measured by streak photography.

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[1] *G. L. Moss, P. H. Netherwood, and R. E. Franz, "Fracture of a Tungsten-Nickel-Iron Alloy with Stress Waves", Bull. Am. Phys. Soc., Vol. 21, No. 11, Stanford, 1 Dec 76, p. 1310.*

[2] *Private communication, T. C. Myhre, Oak Ridge Y-12 Plant, Oak Ridge, Tenn., May 1976.*

[3] *L. M. Barker and R. B. Hollenbach, "Laser Interferometer for Measuring High Velocities of Any Reflecting Surface", J. Appl. Phys., Vol. 43, No. 11, 1972, pp. 4669-75.*

In Hugoniot measurements on rolled homogeneous armor which were performed earlier[4] the elastic-wave velocity in test specimens was measured by electrical contactors at the impacted surface and quartz gages on the back surface; in subsequent VISAR experiments the arrival time of the elastic wave at the free surface served as a reference from which the impact time was determined. Quartz-gage measurements on the tungsten alloy (see example in Figure 1) suggested that the precursor-wave front is reasonably well defined and could serve as a similar reference. However, later VISAR measurements of free-surface velocity (see Figure 2) did not reveal a well-defined front for the precursor wave, and Figure 3 suggests that precursor detail was different in each of the three VISAR experiments. Consequently, VISAR results did not provide the anticipated reference by which the impact time could be determined, and without an impact time the plastic-wave velocity could not be calculated. However, the beginning or toe of the precursor was well defined in each VISAR measurement, so quartz-gage measurements were re-examined to learn if this feature of the precursor could serve as an alternate reference.

Re-examination of quartz-gage signals revealed details which had been overlooked in the initial reduction of data. A low amplitude toe was found and included as part of the precursor (see Figure 1). The velocity of this toe was 5.05 km/s which closely corresponded to the elastic-wave velocity of 5.08 km/s measured in quartz-thumper tests (technique described in Reference 4, pp. 12-13). Previously, poor agreement between the precursor velocity and the velocity from quartz-thumper measurements had been a source of concern. As part of the re-examination, impact obliquity was removed from the measured signals. Quartz gages were 12.7mm in diameter and 2.0mm in thickness (with a 3.0-mm wide guard ring), and nonsimultaneous impact over the effective gage area increases the risetime of the signal and tends to obscure detail. The procedure for removing obliquity consists of estimating the correct signal and reintroducing obliquity in a calculated signal; successive adjustments of the estimated signal bring the calculated and measured signals into agreement. Removing impact obliquity always yielded a three-wave structure in the precursor as shown by the dotted profile in Figure 1. There is concern, though, that poor coupling between the quartz gage and specimen surface might suggest more structure than is actually present. It is conceivable that the low amplitude toe could result from areas of initial contact, and that the apparent second wave could occur when free-surface motion closes small interface gaps remaining between the specimen and gage. Unfortunately, further tests with improved coupling between the specimen and quartz gage were not performed.

Structure in the precursor contributes to the measurement problems. This structure is assumed to be associated with the two-phase nature of

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[4] *G. E. Hauver, "The Alpha-Phase Hugoniot of Rolled Homogeneous Armor", BRL Memo. Rpt. 2651, August 1976 (AD #B012871L).*

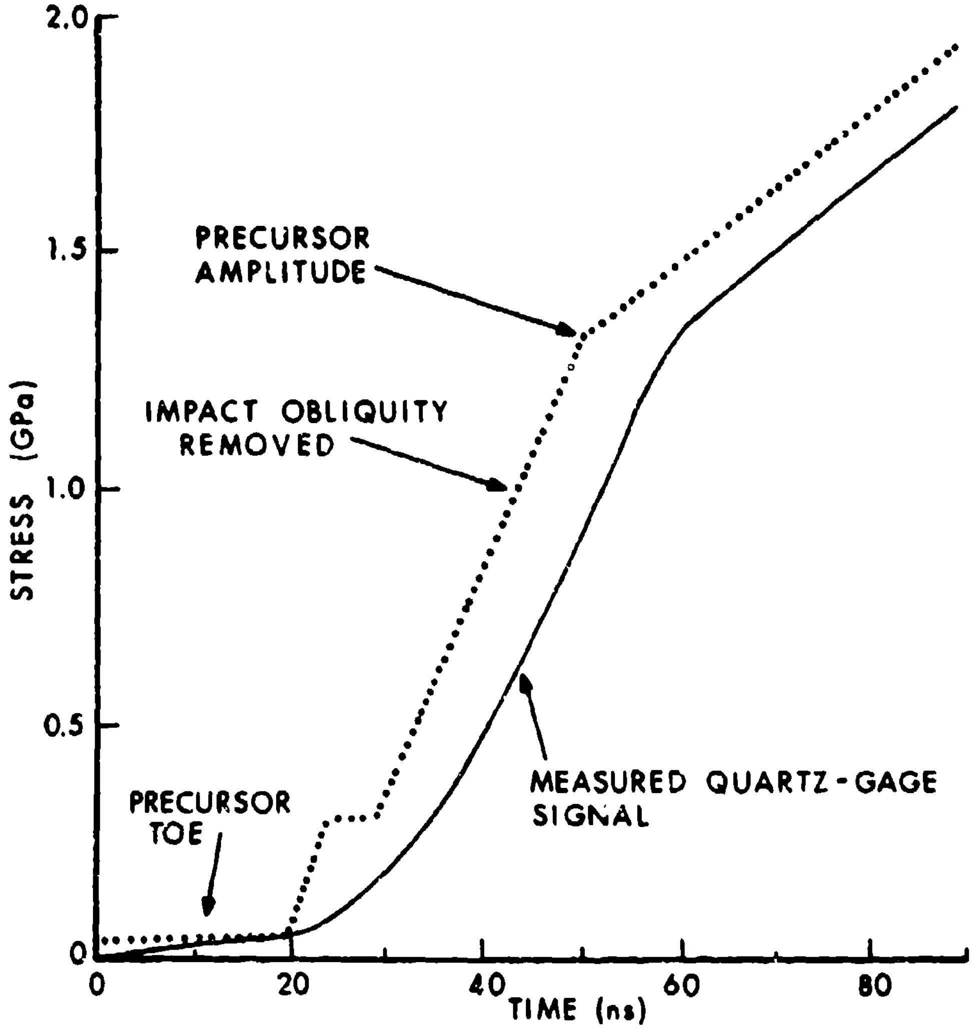

Figure 1. Precursor Profile from a Quartz-Gage Measurement.

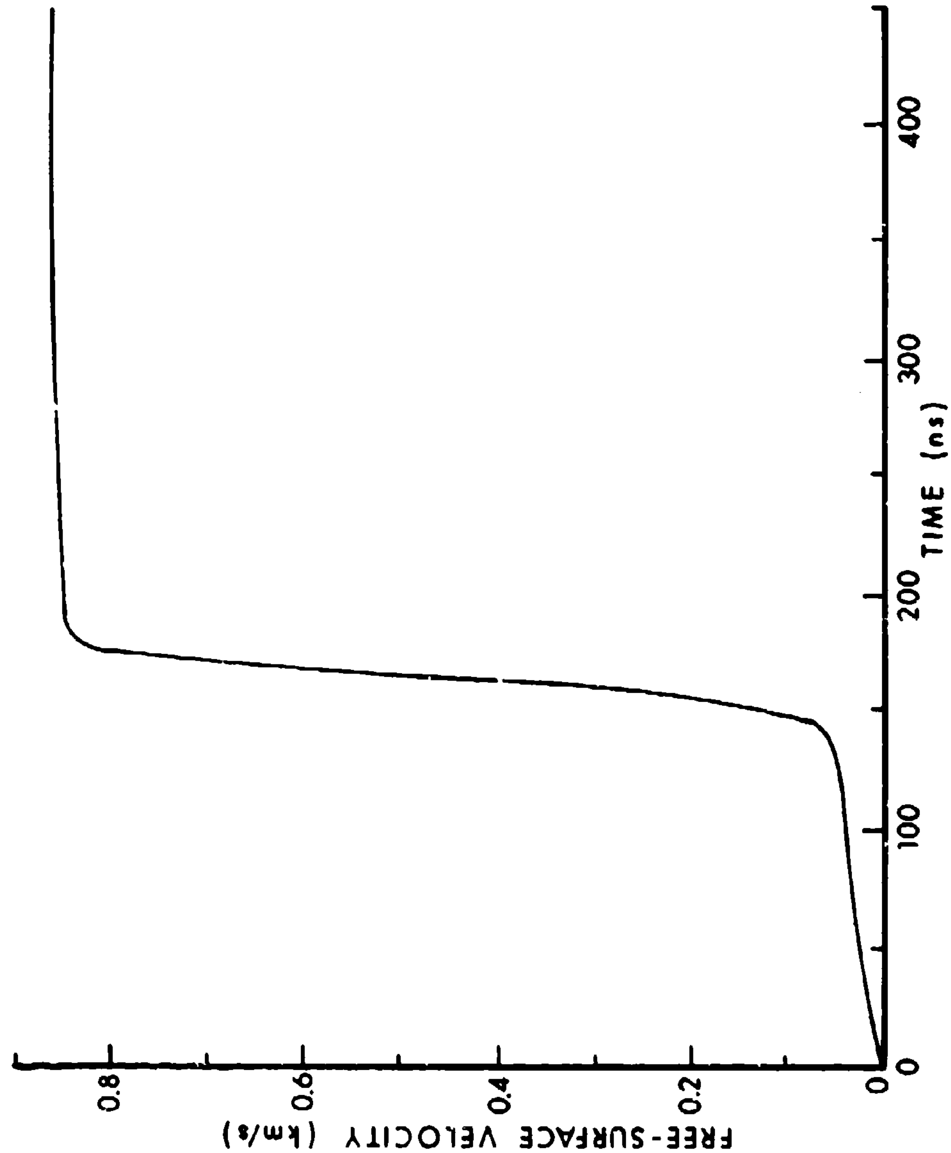

Figure 2. Velocity-Time Profile from the VISAR Test at 32.7 GPa.

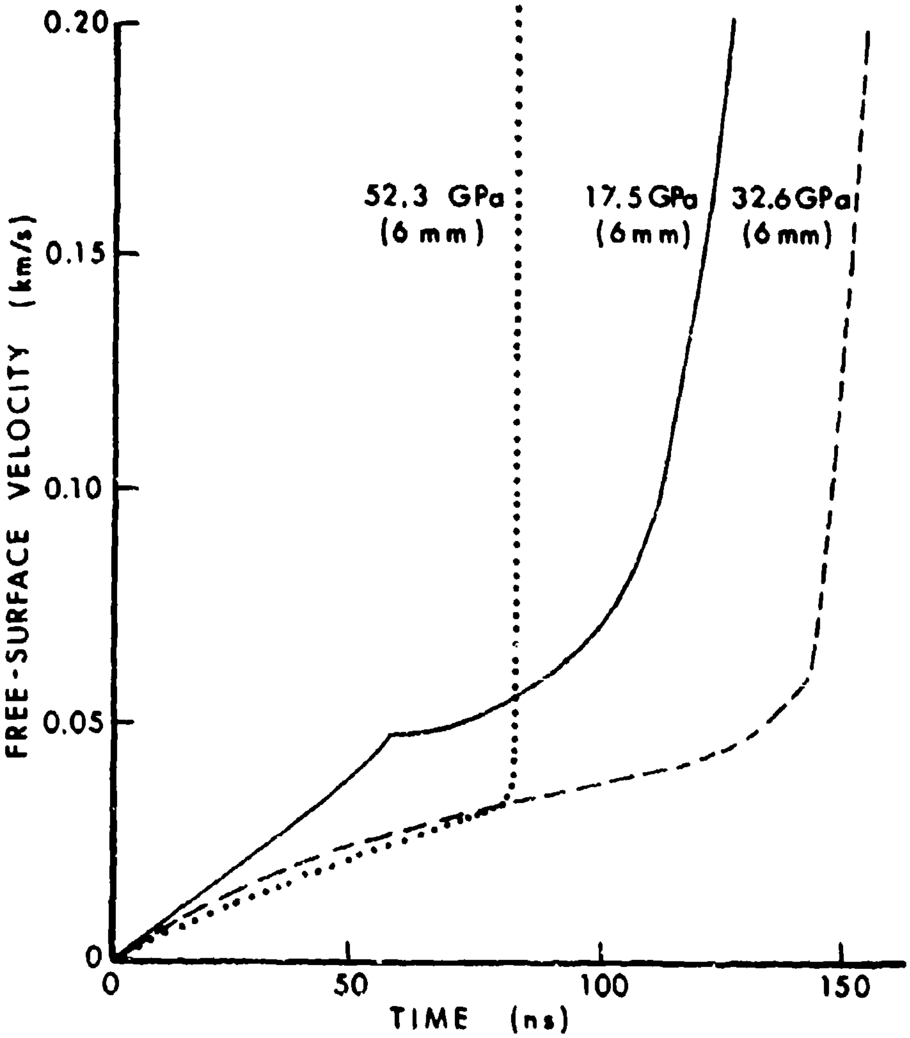

Figure 3. Precursor Profiles from VISAR Measurements.

the alloy. The tungsten and matrix have different shock properties which probably impart roughness to the shock front and a spatial variation of velocity at the onset of free-surface motion. The laser beam of the VISAR focuses to a spot approximately 0.1mm in diameter; this focal area is large enough to include from three to ten tungsten particles and the surrounding matrix, but is small enough to cover areas in which the tungsten and matrix can deviate significantly from the mean distribution. Different distributions of tungsten and matrix in the focal area may account for different detail in precursor profiles that emerge from VISAR measurements. Another problem arises when fringe contrast is degraded by velocity variation within the focal area[5]. In addition, fringes are seriously degraded at the plastic-wave front where the free-surface velocity increases rapidly and the fringe frequency exceeds the frequency response of the instrumentation. As a consequence of various sources of uncertainty, VISAR results were used primarily to detect arrival of the plastic wave at the free surface.

III. DATA REDUCTION, RESULTS, AND DISCUSSION

The plastic-wave Hugoniot is based on several sources of data. In the low-pressure region where a precursor exists, the plastic-wave velocity was provided by VISAR measurements and was based on the assumption that the beginning of the VISAR signal corresponds to the beginning of the quartz-gage signal. This correspondence was not proved but now seems reasonable since the focal area of the laser beam is large enough to include areas of both tungsten and matrix. The impact velocity was measured by a sequence of electrical contactors, and the symmetrical impact condition established the particle velocity, u_p, as one-half the impact velocity. Data for the precursor are needed to establish the state of material ahead of the plastic wave and were provided by quartz-gage measurements, with the precursor stress, σ_e, located at the final knee of the stress-time profile. The precursor velocity, U_e, was evaluated at the midpoint of the major front in the precursor profile, which is the front or step which rises to the final knee at which the stress is assigned. The particle velocity, u_e, is obtained from the conservation of momentum relationship, where

$$u_e = \sigma_e/\rho_o U_e,$$

where ρ_o is the initial density, 17.068 Mg/m^3. Pressure in the plastic wave σ_p, was provided by the conservation of momentum relationship,

$$\sigma_p - \sigma_e = \rho_e U_p \, (u_p - u_e),$$

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[5]J. R. Asay and L. M. Barker, "Interferometric Measurement of Shock-Induced Internal Particle Velocity and Spatial Variations of Particle Velocity", J. Appl. Phys., Vol. 45, No. 6, 1974, pp. 2540-6.

where U_p is the plastic-wave velocity relative to the material into which the wave advances, and ρ_e is the density of that material. The density, ρ_e, comes from the conservation of mass relationship

$$\rho_e = \rho_o U_e/(U_e - u_e).$$

If any of the precursor structure is associated with specific areas of the test specimen, then the usual data reduction based on quartz-gage area is somewhat suspect. Fortunately, either neglecting the presence of a precursor or introducing reasonable data for it has only a minor influence on the plastic-wave Hugoniot, and using reasonable data was selected as the better choice. At pressures above the two-wave region, the conservation of momentum relationship becomes,

$$\sigma_p = \rho_o U_p u_p,$$

where ρ_o is again the initial density. The shock velocity, U_p, is based on transit time measured by streak photography. At these higher pressures which are obtained by the impact of an explosively accelerated metal plate, the test specimen is placed on a buffer material which receives the impact, and the free-surface velocity of the buffer is measured. The particle velocity, u_p, is obtained by an impedence solution[6] based on the release adiabat calculated for the buffer material.

Hugoniot data for the plastic wave are plotted in Figure 4 and listed in Table I. The data from VISAR measurements at low pressures fall in line with data from streak camera measurements at high pressures, with the relationship between shock velocity, U_p, and particle velocity, u_p, given by the expression,

$$U_p = 3.744 + 1.522\, u_p,$$

where the velocity unit is km/s. A range, 4.88 to 5.05 km/s is indicated for the precursor velocity. The velocity, 5.05 km/s, is at the toe of the precursor; the velocity, 4.88 km/s, is at the midpoint of the major front in the precursor and is listed in Table I as the precursor velocity, U_e.

Plastic-wave data commonly extrapolate to a value near the bulk velocity at room temperature and pressure. The Oak Ridge Y-12 Plant reports[7] Elastomat data which yield a bulk velocity of 3.39 km/s, and ultrasonic data which yield a bulk velocity of 3.98-4.01 km/s. The plastic-wave data

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[6] *J. M. Walsh, M. H. Rice, R. G. McQueen, F. L. Yarger, "Shock-Wave Compression of Twenty-Seven, Metals, Equations-of-State of Metal", Phys. Rev., Vol. 108, 1957, 196-216.*

[7] *R. E. Oakes, Jr., and W. M. Moyer, "A Review of Techniques Used to Characterize Cemented Tungsten Alloys for Penetrator Applications", Oak Ridge Y-12 Plant Report Y-2083, September 1977.*

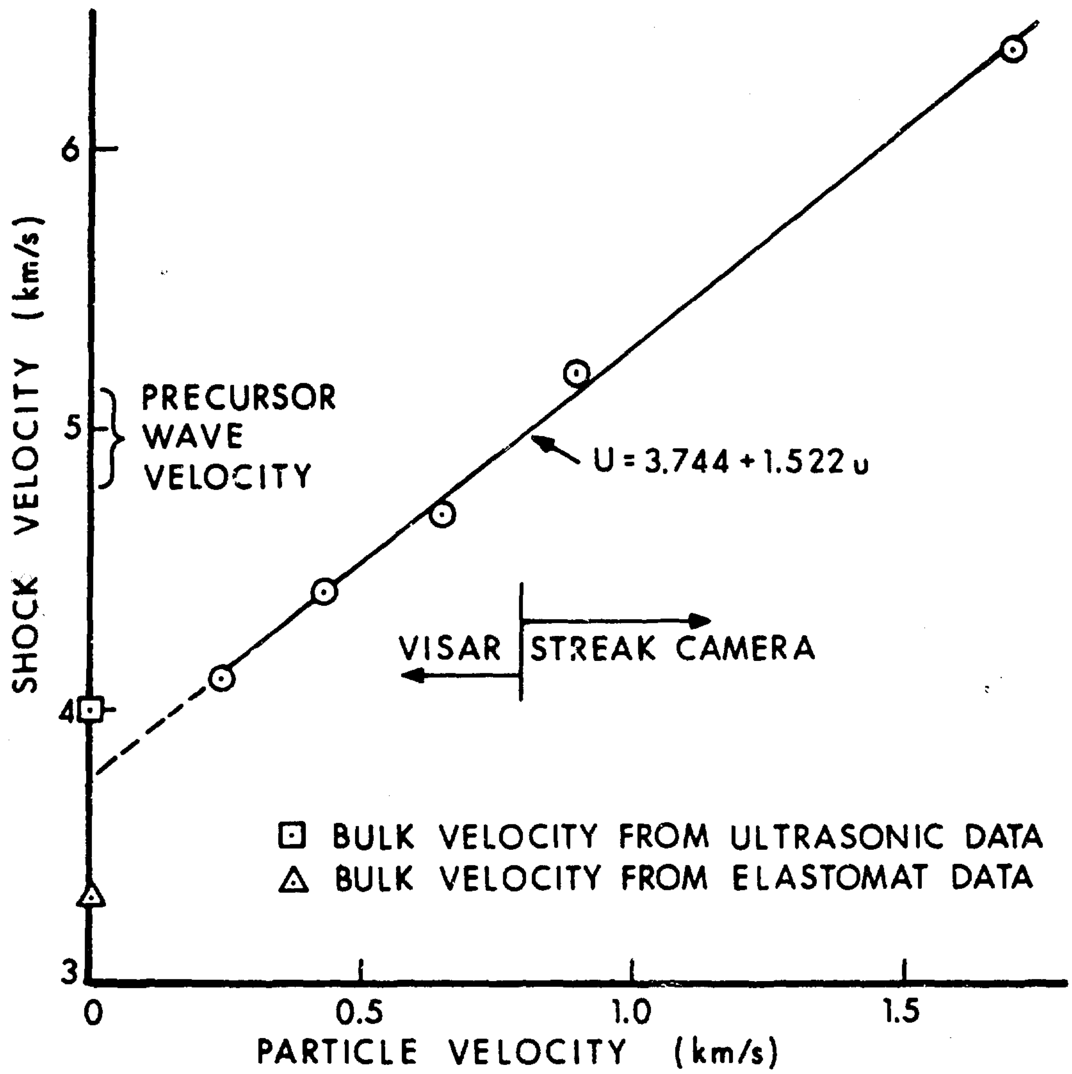

Figure 4. The Hugoniot for 90W-7Ni-3Fe Tungsten Alloy.

extrapolate to 3.744 km/s which is nearly midway between values from Y-12 data. It is noted that the longitudinal velocity is in close agreement with the velocity at the toe of the precursor wave observed in Hugoniot measurements; this suggests that the interpretation of ultrasonic results may have been complicated by the two-phase nature of the material.

TABLE I. HUGONIOT DATA FOR THE 90W-7NI-3FE TUNGSTEN ALLOY

U_e km/s	u_e km/s	σ_e GPa	U_p km/s	u_p km/s	σ_p GPa
4.880	0.023	1.9	4.100	0.245	17.5
4.880	0.016	1.3	4.418	0.430	32.6
4.880	0.016	1.3	4.680	0.652	52.3
			5.186	0.900	79.7
			6.325	1.709	184.5

Swaging causes the matrix of this alloy to become strain hardened while the tungsten particles undergo little change until a high degree of swaging produces some distortion. If precursor structure is related to the two-phase nature of the alloy, then swaging suggests a means for selectively altering the material while observing the influence on the precursor. One impact experiment was performed using a quartz gage to observe the precursor from a 3.0-mm thick specimen of unswaged alloy supplied by the Oak Ridge Y-12 Plant. The precursor was found to be altered with the amplitude of the middle wave enhanced and the final knee increased to 2.6 GPa which is almost 37 percent higher than the corresponding amplitude in 25-percent swaged material. This result had not been anticipated and a hardness measurement revealed that specimens were much too hard to be unswaged. The supplier could not identify the material actually delivered, and since it is difficult to determine the degree of swaging accurately by an examination of physical properties, work on this material was discontinued.

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1. G. L. Moss, P. H. Netherwood, and R. E. Franz, "Fracture of a Tungsten-Nickel-Iron Alloy with Stress Waves", Bull. Am. Phys. Soc., Vol. 21, No. 11, Stanford, 1 Dec 76, p. 1310.

2. Private communication, T. C. Myhre, Oak Ridge Y-12 Plant, Oak Ridge, Tenn., May 1976.

3. L. M. Barker and R. B. Hollenbach, "Laser Interferometer for Measuring High Velocities of any Reflecting Surface", J. Appl. Phys, Vol. 43, No. 11, 1972, pp. 4669-75.

4. G. E. Hauver, "The Alpha-Phase Hugoniot of Rolled Homogeneous Armor", BRL Memo. Rpt. 2651, Aug. 1976 (AD #B012871L).

5. J. R. Asay and L. M. Barker, "Interferometric Measurement of Shock-Induced Internal Particle Velocity and Spatial Variations of Particle Velocity", J. Appl. Phys., Vol. 45, No. 6, 1974, pp. 2540-6.

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7. R. E. Oakes, Jr. and W. M. Moyer, "A Review of Techniques Used to Characterize Cemented Tungsten Alloys for Penetrator Applications, Oak Ridge Y-12 Plant Report Y-2083, September 1977.

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b. Ballistic Research Laboratory Memorandum Report ARBRL-MR-02987, "The Hugoniot for 90W-7Ni-3Fe Tungsten Alloy", by G. E. Hauver, February 1980, UNCLASSIFIED, AD number B046070L.

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